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NASA TM X- 71113

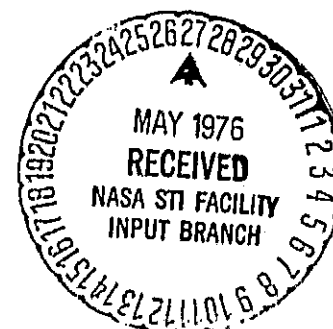# X-RAY OBSERVATIONS
OF THE VELA PULSAR:
STATISTICS AND SPECTRUM

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X-ray Observations of the Vela Pulsar: Statistics and Spectrum

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Abstract

The Vela pulsar (3U0833-45) was observed in the range 2-60 keV
by the GSFC proportional counter experiment onboard OSO-8 with temporal
resolution sufficient to make possible a sensitive search for pulsed
X-rays at the radio pulsar period. A statistical analysis yielded
8 per cent as the 3σ upper limit on the pulsed fraction. The energy
spectrum is fit well by a structureless power law with number index
2.21 ± 0.2 and absorption by a hydrogen column density of N_H =
$(2.9\pm2.0)\times10^{22}$ cm^{-2}.

I.   Introduction

The Vela pulsar (PSR 0833-45) has been identified as a high energy
photon source over a wide range of x-ray energies (Kellogg et al., 1973,
Culhane et al., 1974, Harnden and Gorenstein, 1973, Harnden et al.,
1972) and gamma ray energies (Albats et al., 1974, Thompson et al., 1975).
The first two of these references cited insufficient temporal resolution
to search for pulsed emission at the radio pulsar period (~89 ms).
The others reported pulsed emission at or near this period, although
Moore et al (1974) and Ricker et al (1973) were unable to detect such
pulsations. Between 2-10 keV Rappaport et al (1974) report an upper

limit to a pulsed component at 1/3 the intensity of 3U0833-45. The
fact that PSR 0833-45 is the third fastest known pulsar suggests that
it, like the Crab pulsar, is a likely candidate for the emission of
pulsed x-rays (cf. Pacini, 1971). In this Letter we report an upper
limit to X-ray pulsation and the energy spectrum in an observation of
the Vela pulsar with a proportional counter onboard OSO-8.

II. Experiment

    This observation was performed with a Xenon-filled gas proportional
counter mounted on the spinning portion of the satellite, in alignment
with the positive spacecraft spin axis. The detector has a 5 degree FWHM
circular field of view and net area of 237 cm^2. It has been described
previously (Pravdo et al, 1976) in more detail, and is one of the three
counters comprising the GSFC Cosmic X-ray Spectroscopy experiment (CXS).

    Vela was observed between November 25-27, 1975. For one twenty
minute period we were able to utilize essentially the entire spacecraft
telemetry in order to obtain 1.25 msec temporal resolution for pulse-
height-analyzed events. This "dwell mode" experiment was centered
at 18:47, November 25 UT.

III. Statistics

    The 5 degree circular field of view of the CXS makes it impossible
to separate 3U0833-45 from other nearby areas of enhanced > 2 keV emission.
Although the Vela supernova remnant as a whole is not a source at this
energy, Kellogg et al (1973) suggest two emitting regions, Vela A and
B, in addition to the pulsar. Also 3U0821-42 (Pup A) contributes to
the observed flux, but since it was isolated previously in the detector,

its contribution can be subtracted from the total signal. Other weak sources may be in this area (Forman et al. 1976). The observed signal to background (mainly the diffuse X-ray background) ratio is 0.60, with a signal intensity (2-6 keV) of 2.84×10^{-10} erg cm^{-2}sec^{-1}. The a priori estimate of the fractional contribution to this signal due to 3U0833-45 from its intensity given in the 3U catalogue (Giacconi et al. 1974) is 0.55. From spectral considerations discussed later, we believe this is a lower limit to the source strength.

The data obtained during the dwell mode observation have been folded over a range of periods including that of the radio pulsar. PSR 0833-45 exhibited a discontinuity in its spin down rate near the beginning of October, 1975, and the latest determinations of the period and time rate of charge of period are used (Manchester et al 1976). If the X-ray pulse width is as large as 4ms, the data can not be used to discriminate between pulse periods deviating from the radio period by as much as 0.3μs. The 1.25 ms resolution allows us to bin the folded data into as many as 70 independent bins. When the folded data are χ^2- tested against a model in which the number of counts in each bin is Poisson-distributed around the average value, no significant deviations from an acceptable value of χ^2 are found.

This result can be interpreted in terms of an upper limit to the pulsed fraction from the source in the following manner. Boldt et al. (1970) have given an expression for the average deviation of χ^2 from its expectation value when the test described above is performed, and when the data contain a pulsed component. This deviation is given by:

$$\Delta \chi^2 = (\frac{f}{1+f})^2 (\frac{1-\beta}{\beta}) N_T , \tag{1}$$

where f is the pulsed fraction, β is the pulse duty cycle, and N_T is the total number of counts. If the number of temporal bins $K \gtrsim 40$, and the data are truly nonpulsed, the expectation value for χ^2 is $(K-1)$ with variance $(2K-1)$. The expression for $\Delta \chi^2$ in equation (1) should then be added to $(K-1)$ to obtain the expected value of χ^2 if the data are pulsed. However, if no significant deviation of χ^2 from $(K-1)$ is observed, it is not correct to determine the value of f which would have produced a 3σ change in χ^2, and identify this with the 3σ upper limit to the pulsed fraction. The variance of the relevant distribution (whose expected value is $(K-1) + \Delta\chi^2$) has been calculated and is

$$\sigma_f^2 = (2K-1) + 4 \Delta\chi^2 (1+\epsilon)$$

where $\epsilon = (\frac{f}{1+f})(\frac{1-2\beta}{\beta})$. It is clear that since σ_f^2 is larger than the variance for zero pulsed fraction, the statistical significance of any upper limit to the pulsed fraction is reduced. Figure 1 shows pulse fraction upper limits at the 3σ confidence level versus duty cycle for energies between 2-20 keV. The duty cycle interval displayed extends from the radio duty cycle 0.04 (Downs et al. 1973) to the gamma ray duty cycle ~ 0.2 (Thompson et al 1975). Presumably, the x-ray duty cycle falls between these two values.

IV. Spectrum

The spectrum shown in Figure 2 is obtained from data taken at arbitrary times in the 3-day exposure. It represents approximately

1200 seconds effective time on source. The method of spectral analysis
has been described in an earlier work (Pravdo et al. 1976). Above 20
keV the source signal falls into the background, but no cutoff is observed.
The spectrum is fit well by a power law of number index 2.21 ± 0.2 with
interstellar absorption (Brown and Gould, 1970) by a hydrogen column
density of $N_H = (2.9 \pm 2.0) \times 10^{22}$ cm^{-2}. This structureless power-law
spectrum is similar to that observed for the Crab Nebula (i.e. comparable
spectral index at those energies). There is an indication of spectral
hardening for energies above 10 keV, although these high energy points
are statistically consistent with the single power law.

An analytical approximation to a thermal spectrum with gaunt
factor gives a less acceptable fit (5% probability that this model
would yield the data). The best fit thermal temperature is 11 keV with
negligible absorption.

V. Discussion

In general, the distribution of χ^2 values obtained when data
are tested against the true model is nearly Gaussian if the number of
degrees of freedom (the number of temporal bins in this case) is $\gtrsim$
40. However, there is no reason to believe a priori that the same is
true about the distribution of χ^2 values described in Section III.
Here, data which are assumed to have a finite pulsed fraction are tested
against a model with zero pulsed fraction. Computer simulated experiments
were performed to study this "pseudo" χ^2 distribution more fully. The
distribution was found to be approximately Gaussian, with measured mean
value and variance very close to those calculated in Section III. This
is not surprising since χ^2 is still measuring Poisson deviations from
a mean. In particular, when the simulated data contained a pulsed

fraction equal to the 3σ upper limits displayed in Figure 1, less than 1% of the trials resulted in a χ^2 value equal to or less than the value of χ^2 observed in the Vela data. Therefore these 3σ upper limits can be interpreted in the usual manner. These simulations also showed that the lower "3σ" upper limits obtained if the variance of the normal χ^2 distribution is used, are incorrect.

This observation lowers to 8% the upper limit to pulsed 2-10 keV x-ray emission with the radio duty cycle. If the X-ray duty cycle is as large as the gamma ray, the upper limit is somewhat larger. The solid lines in Figure 1 demonstrate this for two energy ranges.

The spectrum shown in Figure 2 is remarkably similar in form to, although of a higher intensity than, that obtained by Kellogg et al (1973) with a detector having a much smaller field of view. The absorption measured here is larger than that characteristic of the Vela region in soft x-rays (Seward et al 1971, Gorenstein et al 1974) but consistent with the determination of Culhane et al (1974). This spectral similarity could indicate that essentially all the observed signal originates at 3U0833-45 but at a level which may be as high as twice the 3U value. The possibilities of source intensity variability and absorption intrinsic to the source have been discussed in the preceeding reference. The dashed lines in Figure 1 shows the resultant pulsed fraction if the total CXS flux is from the pulsar.

Regardless of the fraction of the signal coming from the pulsar, the pulsed flux upper limit is the same. From 2-10 keV for the two extremes of duty cycle, this pulsed flux upper limit is 2.0×10^{-11} erg

$cm^{-2}s^{-1}$ ($\beta = 0.04$) and $4.8x10^{-11}$ erg $cm^{-2}s^{-1}$ ($\beta = 0.2$). From 10-20 keV these limits are $2.5x10^{-11}$ erg $cm^{-2}s^{-1}$ and $6.3x10^{-11}$ erg $cm^{-2}s^{-1}$. This result is inconsistent with some models of pulsed emission from pulsars (see Rappaport et al 1974 for discussion) but is still a factor of 2-10 above the predicted pulsed flux in Thompson (1975). In this model for pulsed gamma ray emission the accelerated charges responsible for the radio pulse give rise to gamma rays when forced to leave magnetic field lines which are unable to corotate with the neutron star at the speed of light radius. The pulsed component has a flatter spectrum than the total pulsar spectrum. This last statement is supported by the spectrum measured here, as the extrapolation to gamma ray energies of the flattest spectrum consistent with our data falls a factor of 3 below the intensity reported in Thompson et al. (1975).

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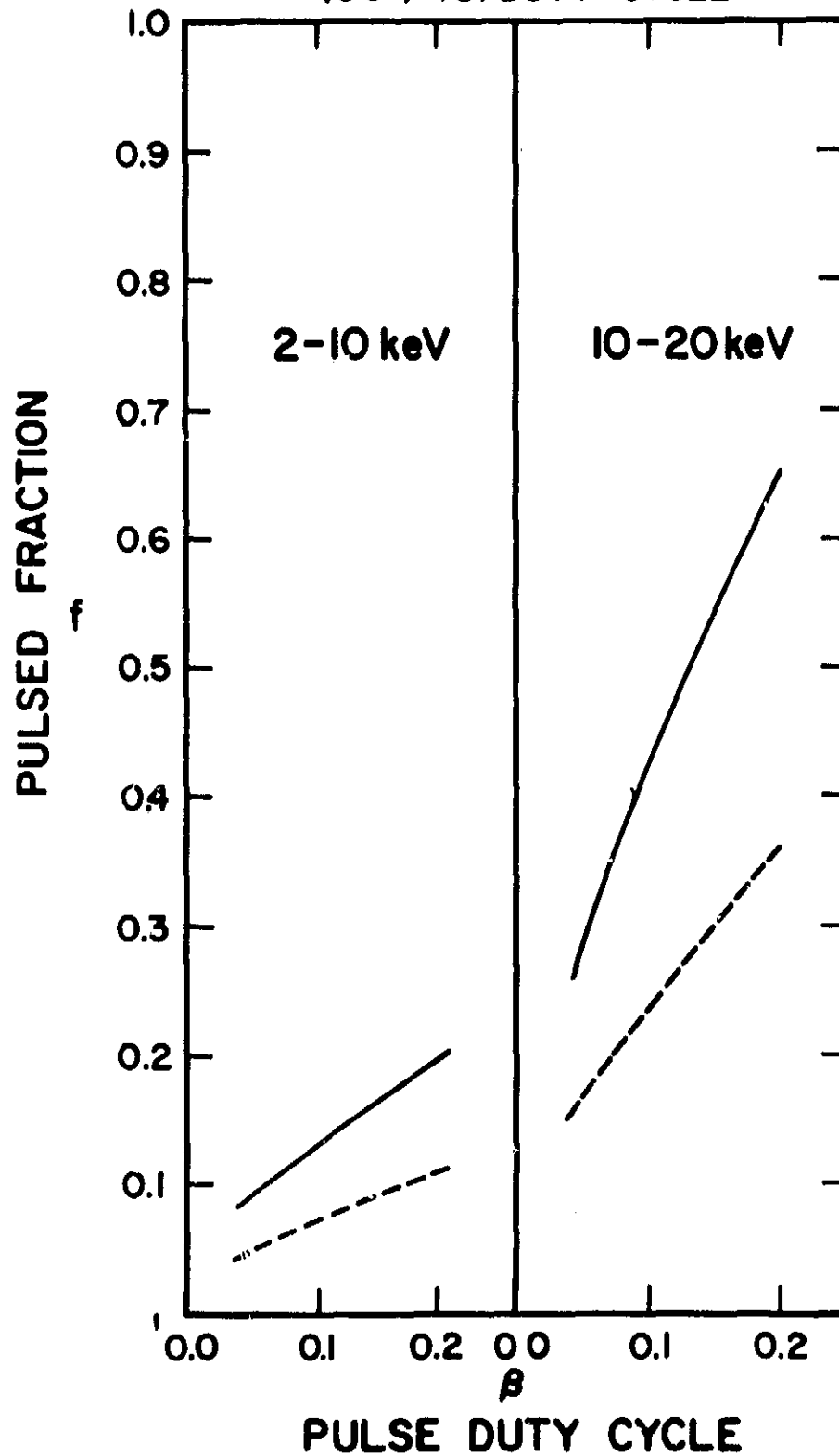Thompson,D. J., Fichtel, C. E., Kniffen, D. A., and Ogelman, H. B.

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FIGURE CAPTIONS

Figure 1.   Pulsed fraction upper limits (3σ) for the Vela pulsar
versus pulse duty cycle for the energy range 2-10 keV
and 10-20 keV.   The solid and dashed lines refer
respectively to the pulsar intensity at the 3U catalogue
level and at the total OSO-8 level.

Figure 2.   The incident X-ray Spectrum from the Velá pulsar.
See text for discussion of other possible contributions
to this flux.

PULSED FRACTION UPPER LIMITS
(3σ) VS. DUTY CYCLE